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Ice fog

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ICE FOG

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by

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PREFACE

This paper on ice fog has been prepared at the U. S. Naval Postgraduate School, Annapolis, Maryland, during the winter and spring terms of 1948, for submission in partial fulfillment of the requirements for the degree of Master of Science in Aerology.

Acknowledgment is made to Professor William D. Duthie for his helpful guidance and advice. The writer is also indebted to Lieutenant Commander Daniel F. Rex, Mr. V. J. Schaefer and others of the General Electric Research Laboratory for suggestions concerning the physics of ice fog formation.

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All times are for 150th meridian.

INTRODUCTION

The subject of this paper is that type of fog peculiar to the polar and sub-polar regions in winter, variously known as ice fog, ice-crystal fog, frost fog, spicule fog, pogonip, or mist. Ice fog, though of common occurrence in arctic and antarctic regions, has not been very widely investigated. Only in rather rare cases have observers attempted to distinguish ice fog from water fog, with the result of course, that records of ice fog are quite sketchy. The investigation reported in this paper was prompted by two things: first, the appearance of two reports (2), (7) on ice fog by Alaskan observers, and second, the belief that information about ice fog and the ability to forecast it, though not of interest to many people up to now, may very well become of considerable interest in the future, especially from a military point of view.

Ice fog is a phenomenon of very cold weather, occurring at temperatures near or below 0° F. In general it occurs when the synoptic situation is dominated by a surface anticyclone. This implies, of course, clear skies, light surface winds, and a sharp surface temperature inversion. Local topographical features exert a considerable effect as well. The temperature at which ice fog forms depends to some extent on the kind of sublimation nuclei present, since the fog forms by the direct sublimation of water vapor in the air onto sublimation nuclei of various kinds.

An objective method of forecasting ice fog at Fairbanks, Alaska is presented, based on the prognostic values of wind, pressure and minimum temperature. A reasonable degree of accuracy seems possible by forecasting on the basis of these elements alone, and a somewhat higher degree of accuracy should be attained by considering such additional factors as cloud cover, humidity, and air mass trajectory.

The data used were meteorological records and fog frequency tables of Alaskan, Siberian, and antarctic stations, with especial attention to the records of Fairbanks, Alaska. A particular study of the winters of 1936-37 and 1937-38 at Fairbanks was made because there were available data from a series of upper air soundings (both aircraft and radiosonde) made at Fairbanks during those winters by a research group of the U. S. Weather Bureau (10). Thus it was possible with the data from these soundings, plus the surface data, and by reference to the Historical Weather Maps (4) prepared by the Joint Meteorological Committee, to study ice fog at Fairbanks in relation to the three-dimensional state of the atmosphere at the times the fog occurred.

This investigation is necessarily not exhaustive, but is presented with the object of stimulating further research into the problem of forecasting ice fog.

CHAPTER I

ICE FOG AS IT OCCURS

1. Definition and Description.

Ice fog is that phenomenon which results from the direct sublimation of water vapor in the air onto sublimation nuclei, filling the air with tiny crystals of ice. This type of fog is the common thing in winter at polar stations, in some places occurring as often as one day out of three or even more often, but it has not been widely investigated as a distinct phenomenon. There are many records and tables of arctic fog, but in almost none of these records can one find ice fog distinguished from its sister, water droplet fog. Reproduced here is a table of the frequency of fog and mist (a common term for ice fog in the arctic) over the pack ice of the Arctic Ocean, one of the few cases where care was taken to record these fogs separately (1). The data shown in Table 1 are from the records of the Maud during the period from June 1923 to July 1925, while she drifted in the pack ice off northeastern Siberia.

FREQUENCY OF FOG AND MIST OVER PACK ICE

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
FOG	4.0	2.0	4.5	2.0	12.5	18.0	24.0	26.5	14.5	4.0	1.5	1.0	114.5
MIST	11.0	6.0	7.5	2.5	5.0	1.0	2.7	0	0	2.0	5.0	9.5	52.2

MAUD (2 years' average)

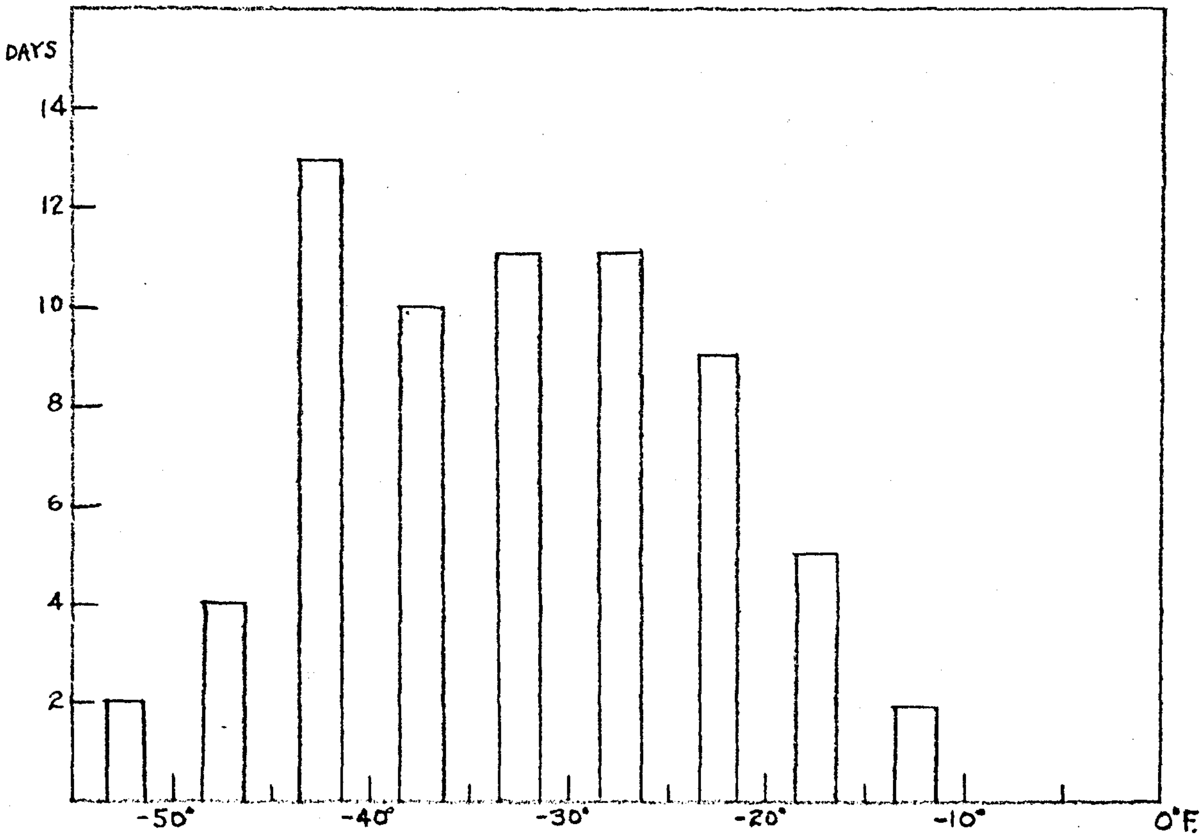
TABLE 1

It can be seen from Table 1 that ice fog is a winter fog. It is primarily of the radiation type, though at some stations an advective factor contributes to its formation. For example, at Anchorage, Alaska Fox (2) reports that a condition favorable to the formation of ice fog there exists when the air reaching Anchorage blows over a nearby inlet, which has some open water even in winter. Sufficient moisture is picked up by the air for saturation to occur when this air passes on to the cold snow surface, with the resultant formation of ice fog.

It is not a sufficient condition for the formation of ice fog that the temperature be below freezing. The thermometer must drop to near or below 0° F. The fogs that occur in the temperature interval between 32° F and 0° F are usually composed of supercooled water droplets, while below 0° F we find fogs composed of tiny needles of ice. There is a considerable temperature overlap, however, in which fogs of either type may occur (or a fog composed of both droplets and crystals may exist). Of interest is this note made by the weather observer at Little America in Antarctica on April 5, 1929 (3).

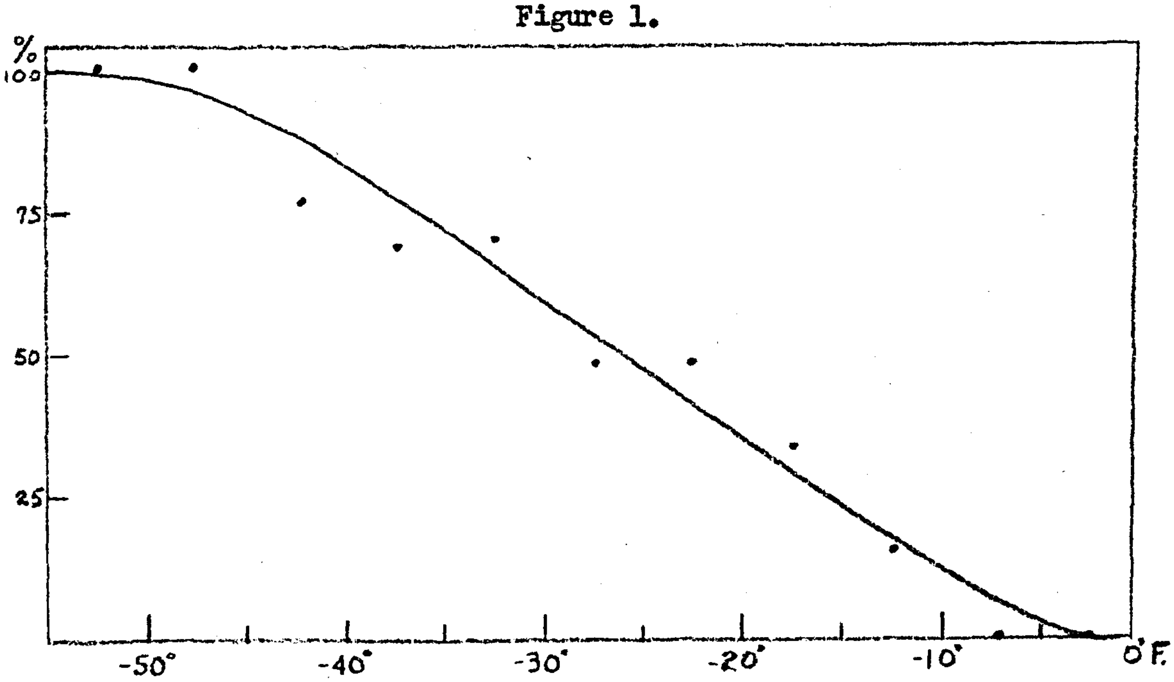
> A fog formed at 7h with a temperature of -28° F. The fog thickened at 9:30 when the visibility was lowered to less than 1000 feet. There is no doubt that the fog was made up entirely of supercooled water particles, being noticeably wet when felt upon the face. In the evening in the beam of a flashlight countless extremely small water particles were plainly visible; a few small flakes of snow were seen floating down at this time also.
>
> A coating of rime about $\frac{1}{4}$ inch thick formed on practically all objects.

Little America was situated on the Ross Ice Shelf not far from the waters' edge (the water being to the north) and frequently experienced advection water fogs rolling in from the Ross Sea. In the above instance, however, the wind preceding and during the fog was light southwesterly (calm to 7 mph) which would seem to rule out the possibility that this fog came off the open water.



TEMPERATURE DISTRIBUTION OF ICE FOG AT FAIRBANKS, ALASKA

Figure 1.



PERCENTAGE DISTRIBUTION OF ICE FOG AT FAIRBANKS, ALASKA,
WITH RESPECT TO TEMPERATURE

Figure 2.

Figures 1 and 2 show the distribution of ice fog with respect to temperature at one inland station. The graphs are based on data for Fairbanks, Alaska in two successive winters.

Figure 1 simply classifies the 67 days with ice fog according to the minimum temperatures for those days. Figure 2 is a graph of the percentage frequency of ice fog on days with a given minimum temperature. For example, on the days when the minimum temperature was within the interval $-25°$ to $-29°$ F, ice fog accurred on 50% of those days. It cannot be said with certainty that the figures are representative, since they are based on a rather small number of days, but we can at least assume that they indicate the general relationship between ice fog and temperature. It is of interest to note that if the temperature falls below $-40°$ F, ice fog is almost a certainty.

Petterssen (8) points out that water fog undergoes a dissipating influence when it exists over a snow surface. The fog tends to evaporate and then recondense onto the snow, because of the difference in vapor pressures over water and over ice (the vapor pressure over ice being smaller). No such effect occurs with ice fog, however. This means that ice fog once formed will persist until the temperature rises sufficiently to evaporate it, or the wind increases and blows it away.

Ice fog is to be distinguished from a phenomenon rather common in polar regions, the occurrence of falling ice crystals. These crystals, which are really a form of snow, sometimes float down so slowly that they may be mistaken for fog particles. The crystals fall in varying intensities, sometimes from apparently clear skies (at least in the Antarctic) so thick at times that they do in effect produce a fog. Quoting again from the notes taken at Little America (April 7, 1929)(3):

A heavy shower of ice crystals prevailed along the surface around 8h, producing faint reddish parhelia of 22° and an upper tangent arc of 22°. The crystal haze was dense enough to make the sun appear faint and lower visibility to less than a mile.

2. Physics of formation.

The exact nature of the process whereby water in its vaporous state changes into one of its denser states (liquid water or ice) is the subject of rather widespread investigation. A considerable variety of theories have been proposed, few of which can explain all the phenomena incident to condensation and sublimation. As far as sublimation is concerned, it is the consensus that some sort of nucleus is necessary to start the formation of an ice crystal and that the size of such a nucleus is of the order of 10^{-4} to 10^{-6} centimeters.

A variety of substances will serve as sublimation nuclei. Schaefer (5) has found that a number of dusts are effective in initiating sublimation. Each substance appears to have its own critical temperature above which it will not be active in the formation of crystals. Most of the particles investigated by Schaefer became active between -10° C and -40° C. This tendency is reflected in Figures 1 and 2, where nearly all the ice fogs fall within this temperature range.

The formation of ice fog then appears to be the result of sublimation onto one or more kinds of nuclei which happen to be present, with some variability in the temperature of fog formation, depending on which kinds of nuclei are available. Oliver (7) has indicated that smoke particles will act as sublimation nuclei, but Schaefer (5) has been unable to induce crystal formation with smoke (although it is effective in initiating condensation).

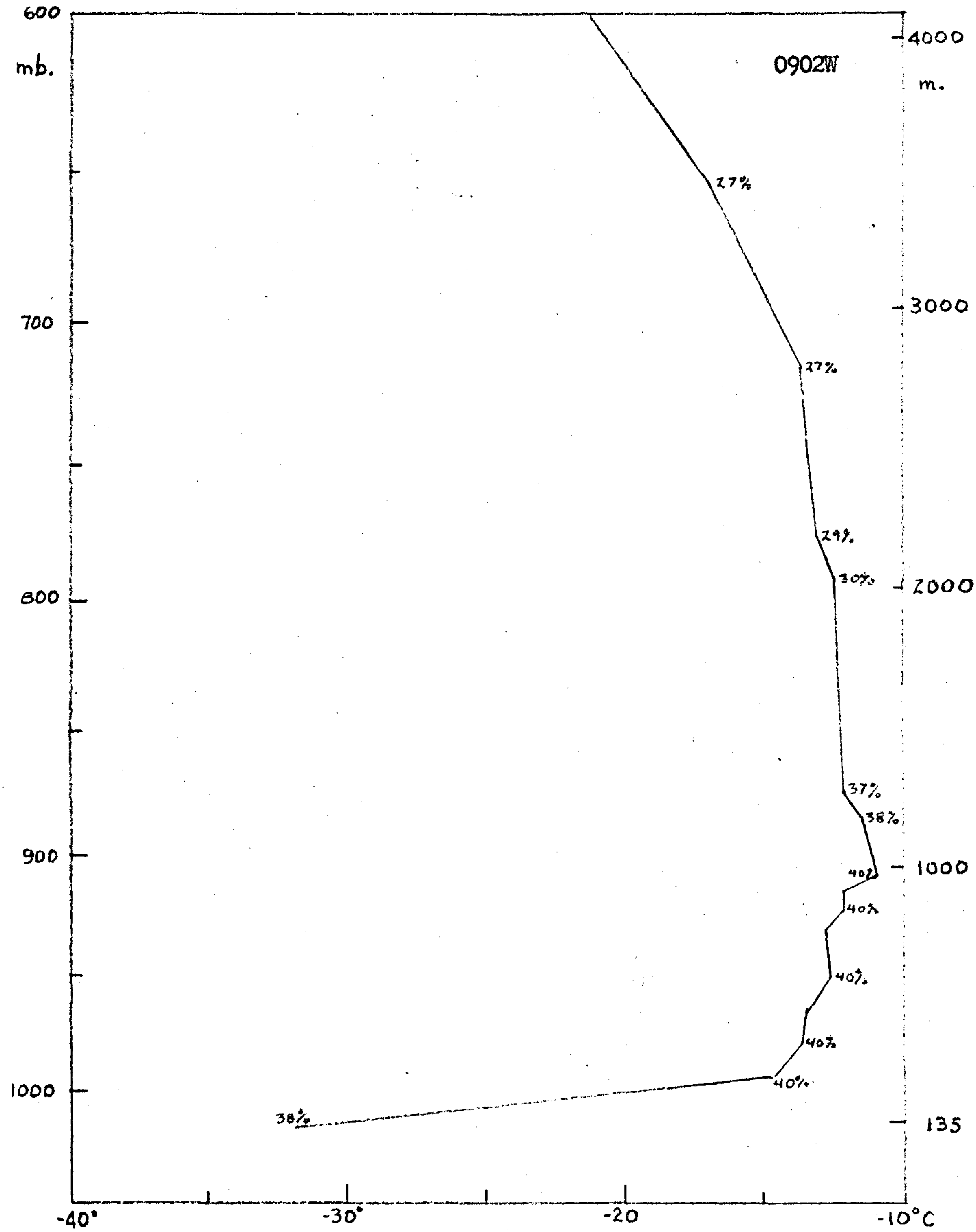
For a given amount of water vapor, visibility will be less if this vapor becomes ice fog than if it becomes water fog. If this were not so, ice fog would hardly be of serious concern, for the moisture content of air at low temperatures is quite small, which means that compared to water fog, relatively little vapor is available for the formation of ice fog.

Fox (2) reports an interesting peculiarity of ice fog which he has observed at Merrill Field, Anchorage, Alaska. It is the delicate balance that exists at times between the existence and non-existence of the fog, a balance so unstable that an airplane warming up on the field may cause the visibility to lower from unlimited to less than half a mile within a period of a few minutes. He offers as possible explanations of this "trigger action" the propeller vibrations, or perhaps particles in the gases of combustion which serve as sublimation nuclei. The effect observed by Fox corresponds closely to the "chain reaction" type of phenomenon which Schaefer (5) has demonstrated in his experiments in artificial nucleation, wherein he found that sublimation, once initiated, is a self-sustaining process.

3. Local factors affecting frequency of ice fog.

It is not easy to generalize about ice fog because of the considerable variation in its frequency from station to station. Coastal stations do not experience ice fog as frequently as do inland stations for the obvious reason that coastal temperatures are moderated by the warming effect of the ocean. But if the ocean is frozen, as in the case of the Arctic Ocean, then the coastal effect will be much less pronounced, or may even be reversed. For example, near the mouth of the Mackenzie River in northwestern Canada "mist" occurs on as many as 20 mornings per month in winter, a frequency that is greater than that at most inland stations. It should be noted that this "mist" is usually not dense enough to be recorded as fog (visibility less than 5/8 mile) but is classified as light fog, or just as very low visibility.

A second significant local factor is station elevation. As noted previously, ice fog is primarily of the radiation type, and as such commonly forms under a surface temperature inversion. An example of such an inversion is shown in Figure 3. It can be seen that the layer of cold air is quite shallow. Within the vertical distance of 170 meters the temperature increases from -32° C to -15° C, or at the rate of 10° C per 100 meters. Inversions more pronounced than this one are not uncommon. But if a station is located at an elevation of 1000 feet or more above the surrounding terrain, it will not be within the very cold layer of air shown at the surface in Figure 3 and will not experience as frequently the low temperatures associated with ice fog. Table 2 (1) gives the frequency of fog and mist (ice fog) at two Canadian stations about 100 miles apart, but at different elevations. Hudson Hope (elevation 1606 feet) lies in a river valley, where conditions are favorable for the drainage of cold air, while Beaver Lodge (elevation 2500 feet) lies above the surrounding countryside. Unfortunately this table does not list ice fog separately from water fog (except that mist indicates light ice fog) but we may reasonably assume that a considerable percentage are ice fogs, for temperatures fall as low as -60° F here (Hudson Hope) in winter.



UPPER AIR SOUNDING AT FAIRBANKS, ALASKA, DECEMBER 2, 1936

Figure 3.

DAYS WITH VERY LOW VISIBILITY DUE TO FOG AND MIST

		Nov	Dec	Jan	Feb	Mar
Beaver Lodge	Fog	0.9	0.6	0.6	0.0	10.2
	Mist	0.0	0.9	0.6	0.0	0.0
Hudson Hope	Fog	20.1	22.3	21.7	19.6	21.4
	Mist	4.5	4.0	4.3	2.2	2.5

Table 2

4. Effect of synoptic situation.

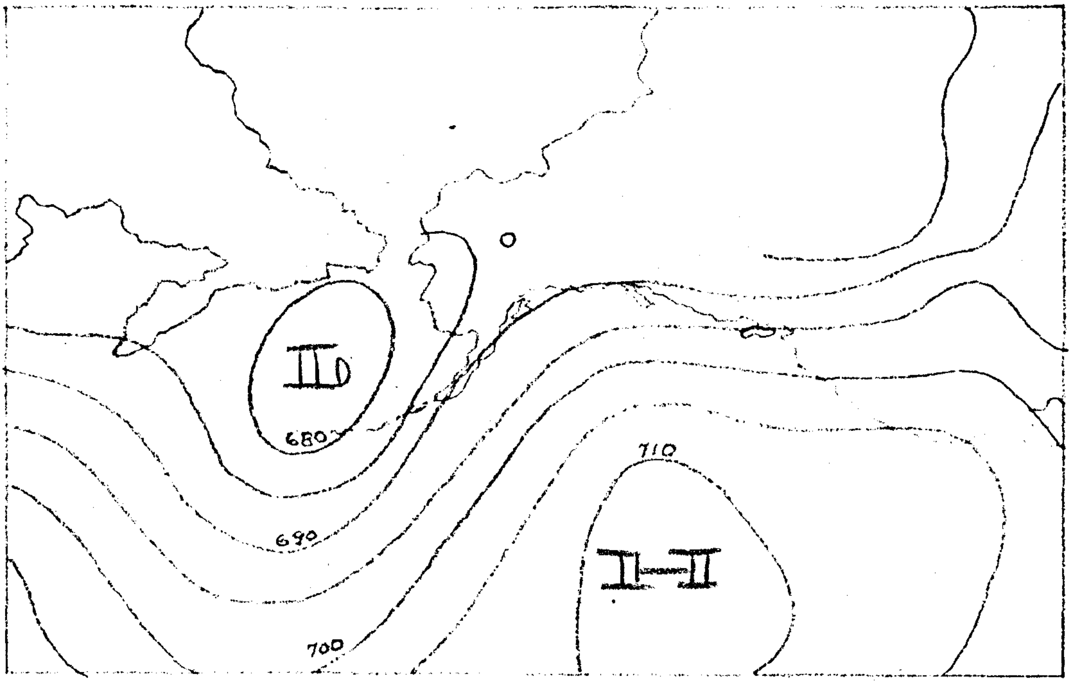
It would be expected that the formation of ice fog depends to some extent on the synoptic situation. As will be indicated below under the subject of forecasting ice fog, the synoptic picture is significant to a considerable degree. In general ice fog will occur in an area of high pressure, with attendant clear sky and cold temperature. The cold temperature is the result of strong surface radiation, producing a steep temperature inversion at the ground, such as was discussed in the previous section. It is not necessary that the air aloft (above the first few hundred feet) be extremely cold to create a favorable situation for ice fog; in fact, if exceptionally cold air moves in over a station it will contain so little moisture that the formation of ice fog is not likely. A much more favorable situation is the presence of air a few hundred feet above the ground which is at a temperature somewhat above 0° F. It will then contain enough water vapor so that when rapid cooling takes place at the ground saturation will result.

A necessary condition in all cases of radiation fog is light wind near the surface. If the force of the wind is as high as Beaufort 3 or higher, turbulent mixing will take place and the surface temperature inversion will be wiped out.

The figures included here illustrate some typical fog and non-fog situations. Figure 4 shows the surface and 10,000-foot maps on a day when light ice fog existed at Fairbanks from early morning until 1900. (The sounding of Figure 3 was taken on this same day). A similar situation is shown in Figures 5 and 6, when light to moderate ice fog persisted most of the day.

It will be noted that the relative humidities on the aircraft soundings do not indicate saturation at the surface. This is due principally to the extreme lag of the hair element of the meteorograph when used at low temperatures. The time lag in the response of hair to changing humidity increases markedly at temperatures below 0° C, becoming almost infinite near -40° C (6). The humidity element of a radiosonde is somewhat more accurate, but here also the soundings do not indicate saturation at the surface when ice fog is present. A contributing factor to the inaccuracy of any humidity element in the presence of ice fog is the difference in humidities with respect to water and to ice. The air may be saturated with respect to ice, while the instrument, being calibrated with respect to water, will indicate something less than saturation. Psychrometer readings taken in the presence of ice fog give relative humidities of or very near to 100 per cent.

A further remark may be made about the accuracy of the soundings, i.e., that the radiosonde fails to indicate the presence of a sharp surface inversion. Figure 7 shows the discrepancy between an aircraft and a radiosonde sounding taken within the same hour. It seems reasonable in this case to believe that the aircraft temperatures are more



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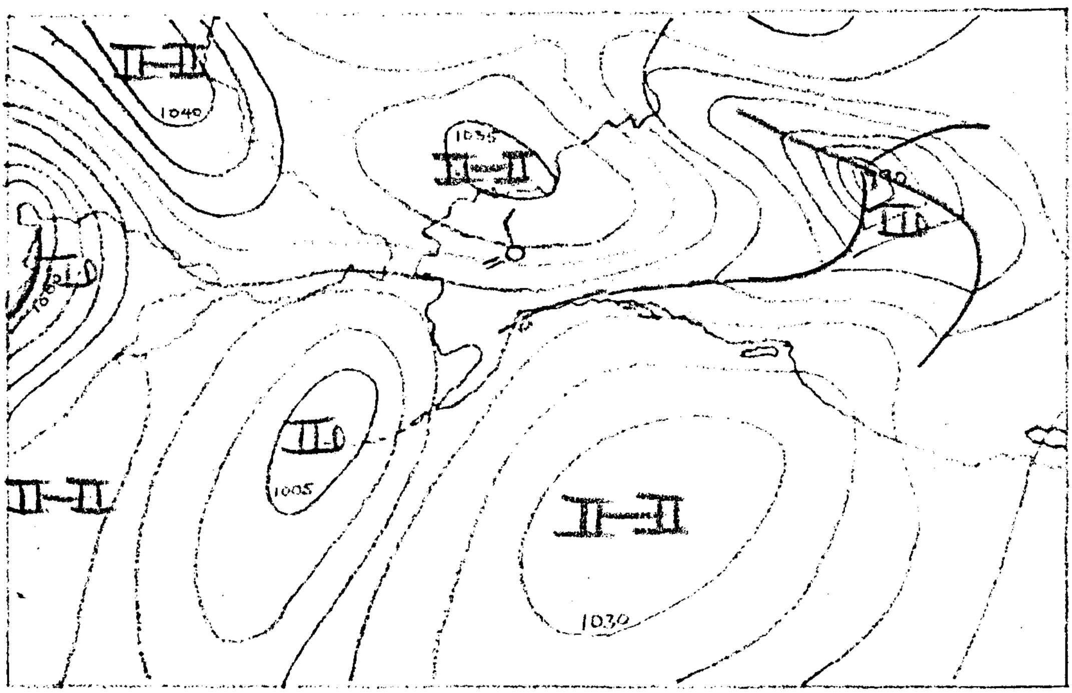
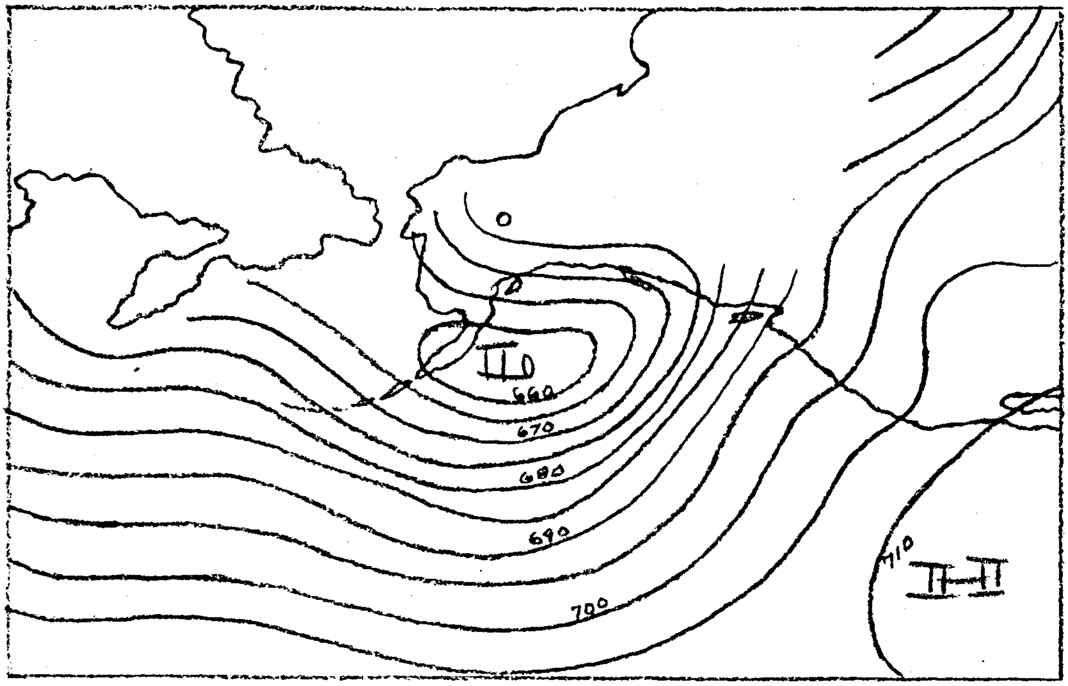


0300W 12/2/36 Sea Level

SYNOPTIC MAPS ON DECEMBER 2, 1936

Figure 4.



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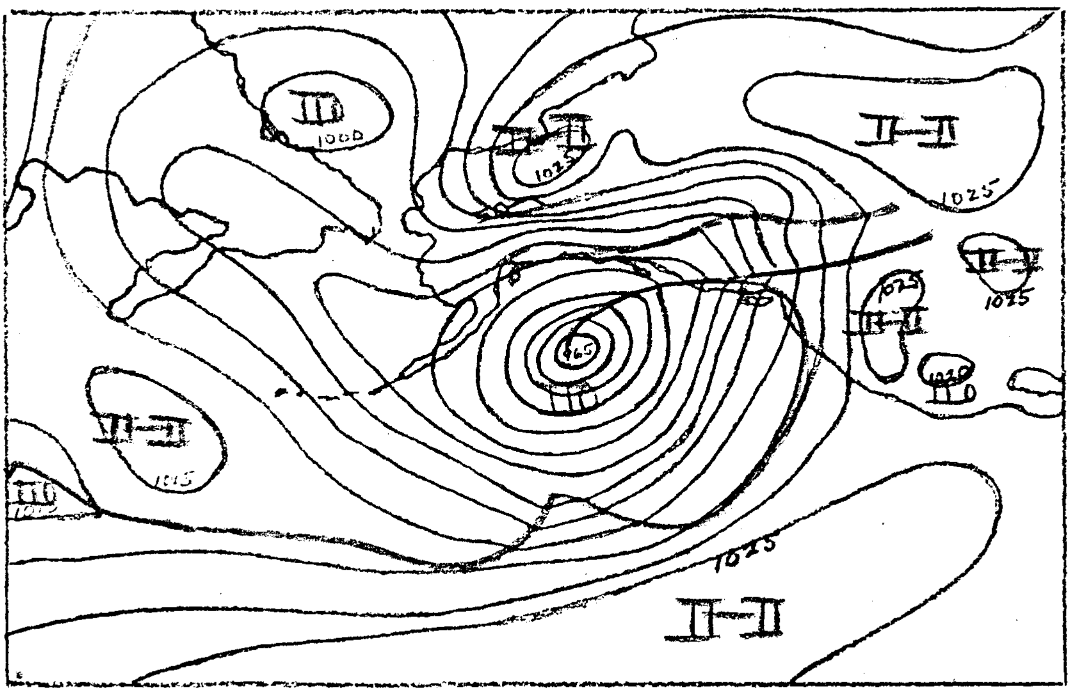

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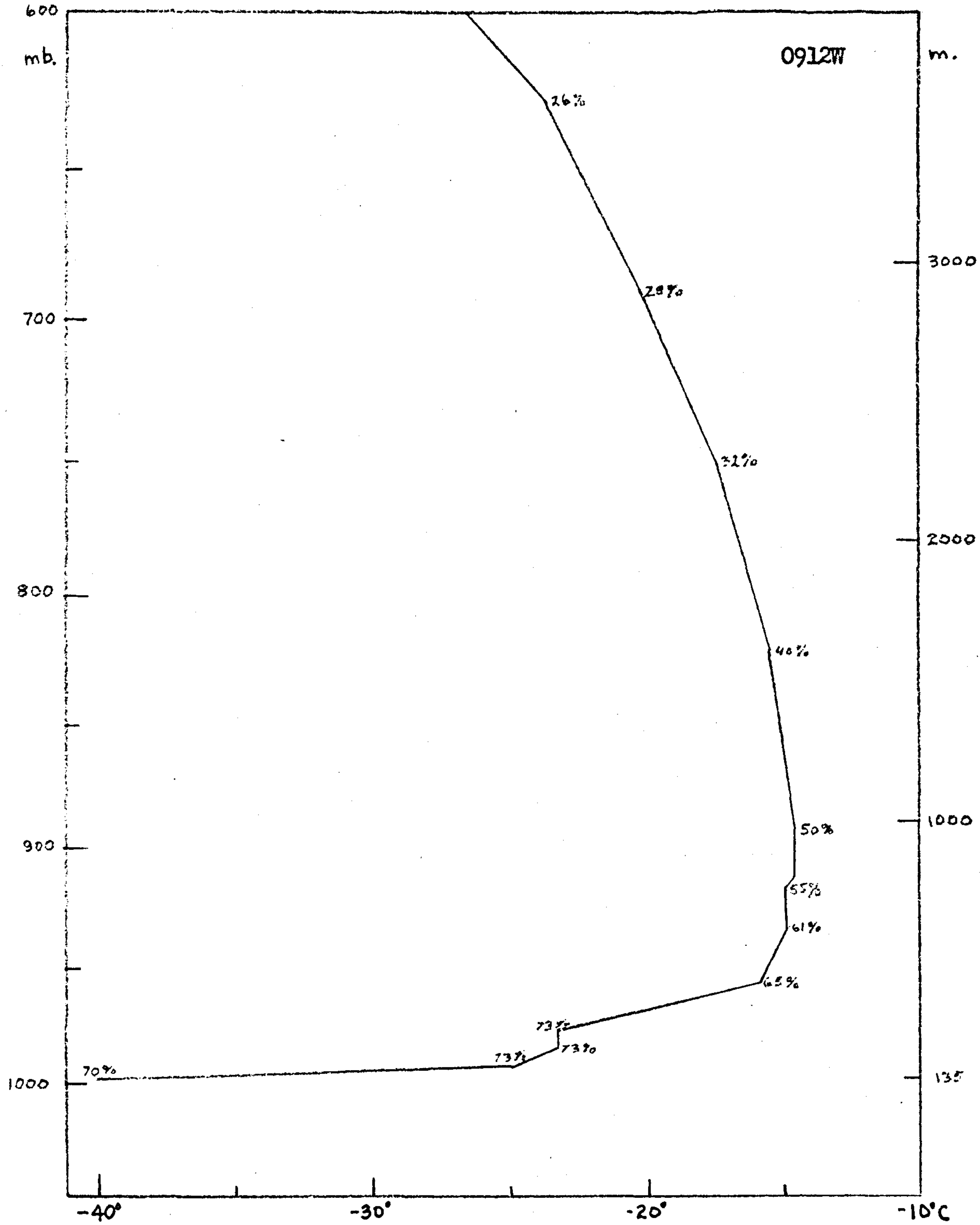
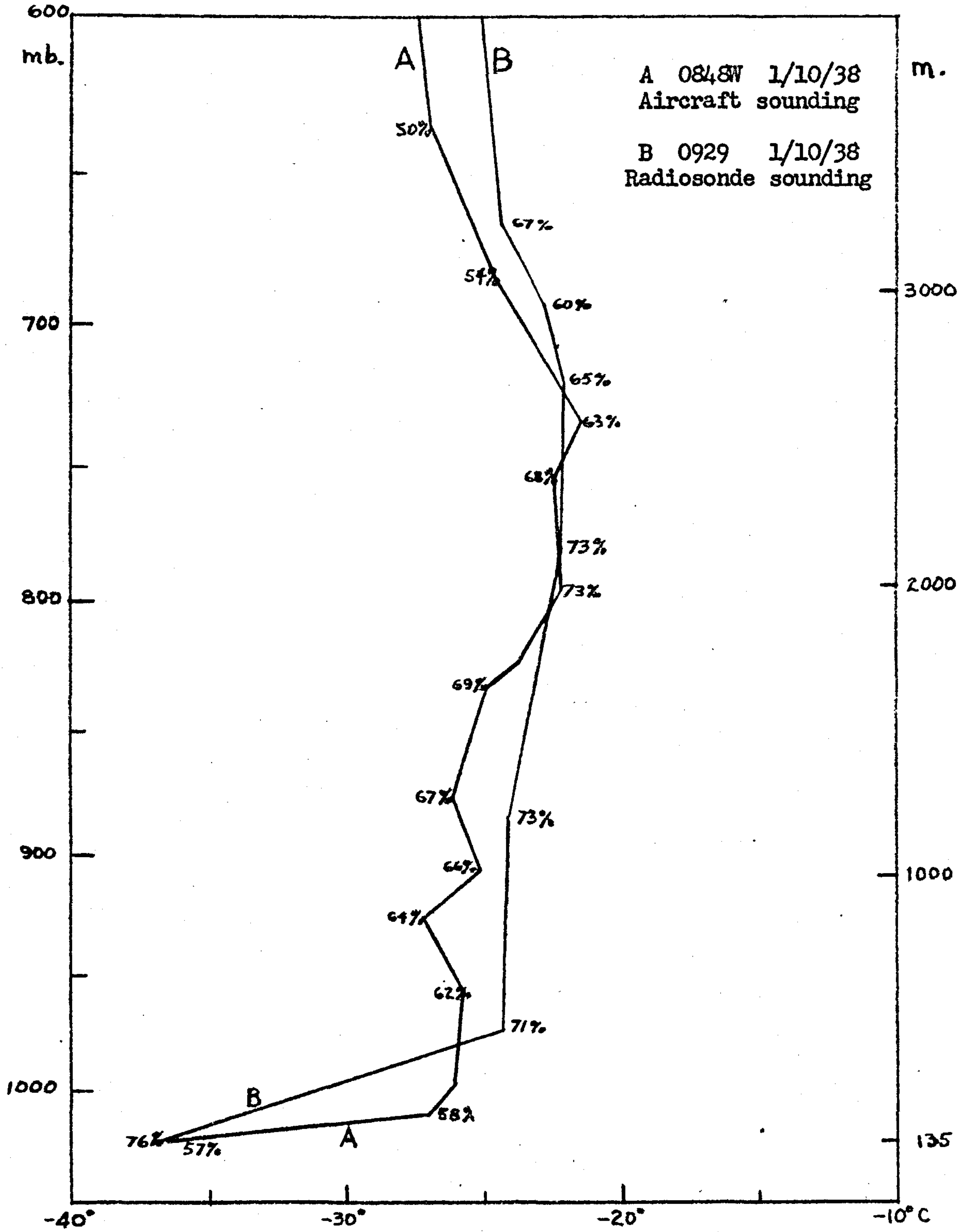
SYNOPTIC MAPS ON DECEMBER 21, 1936

Figure-5.



UPPER AIR SOUNDING AT FAIRBANKS, ALASKA, DECEMBER 21, 1936

Figure 6.



UPPER AIR SOUNDINGS AT FAIRBANKS, ALASKA, JANUARY 10, 1938

Figure 7.

nearly accurate. It must be borne in mind that when these soundings were taken, the radiosonde was in its early stages of development.

Figure 8 shows the synoptic situation at the time of the soundings of Figure 7. Light to dense ice fog persisted throughout the day.

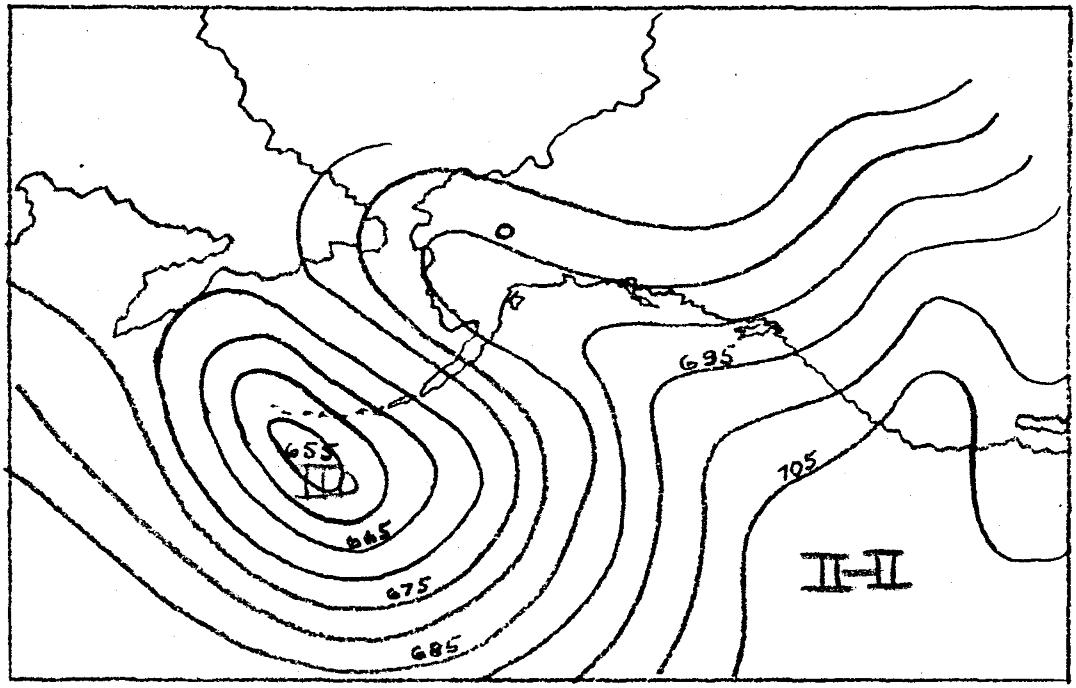
A case of no ice fog is illustrated by Figures 9 and 10. A low pressure area dominates the Alaskan weather; at Fairbanks it is overcast with light snow. But the picture can change quickly, for on the following day ice fog occurred. (Figures 7 and 8).

While it is true in general that ice fog does not occur when a low pressure area is present, some exceptions do occur. Figure 11 indicates such a case. On this day, even though the sky was completely overcast, light ice fog was present through both daylight and darkness.

5. Effect on aircraft operations.

Ice fog does not constitute as serious an obstacle to the safe operation of aircraft as one might imagine. It is the shallowness of most ice fogs which prevents their causing an airport to be completely obscured. Since the depth of the fog seldom exceeds 300 feet, visibility in the vertical remains good enough for a pilot to see the outline of the runways and to distinguish contrasting objects on the ground as he flies over the field. Visibility is poorest during the approach just before touchdown, when the plane is within the fog layer, but with experience a pilot may negotiate this blind space with confidence.

There are exceptions to these conditions, especially at extremely cold temperatures. Ice fog may become so dense that the horizontal visibility will be nearly zero and the vertical visibility, while not zero, may be so reduced that aircraft landings would be inadvisable



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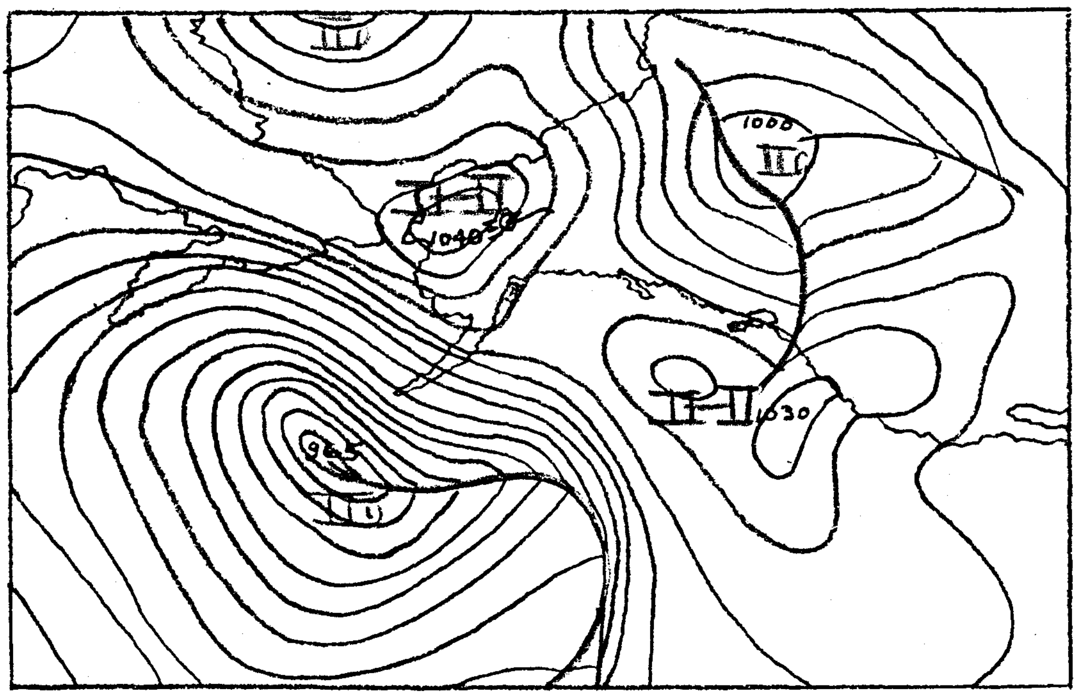
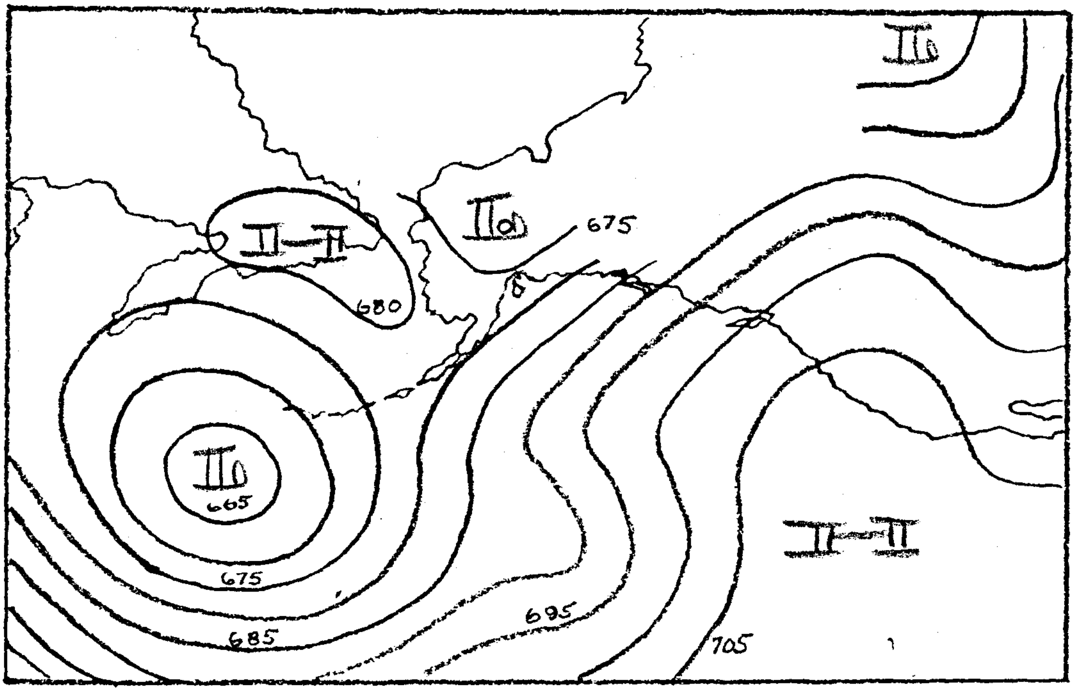


0300GW 1/10/38 Sea Level

SYNOPTIC MAPS ON JANUARY 10, 1938

Figure 8.



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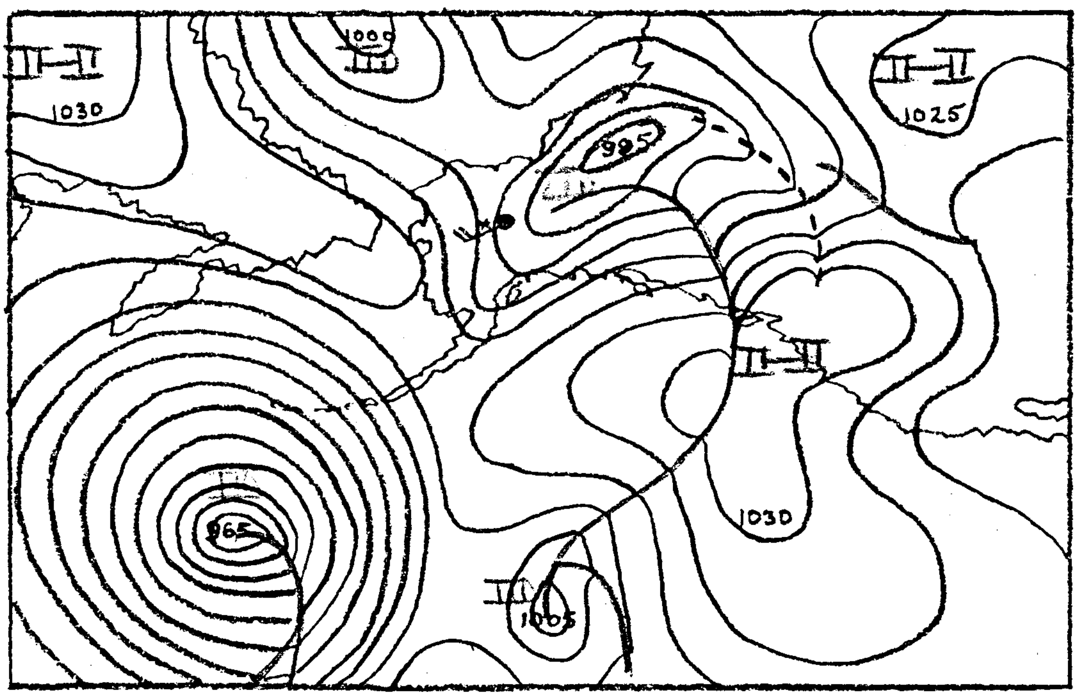
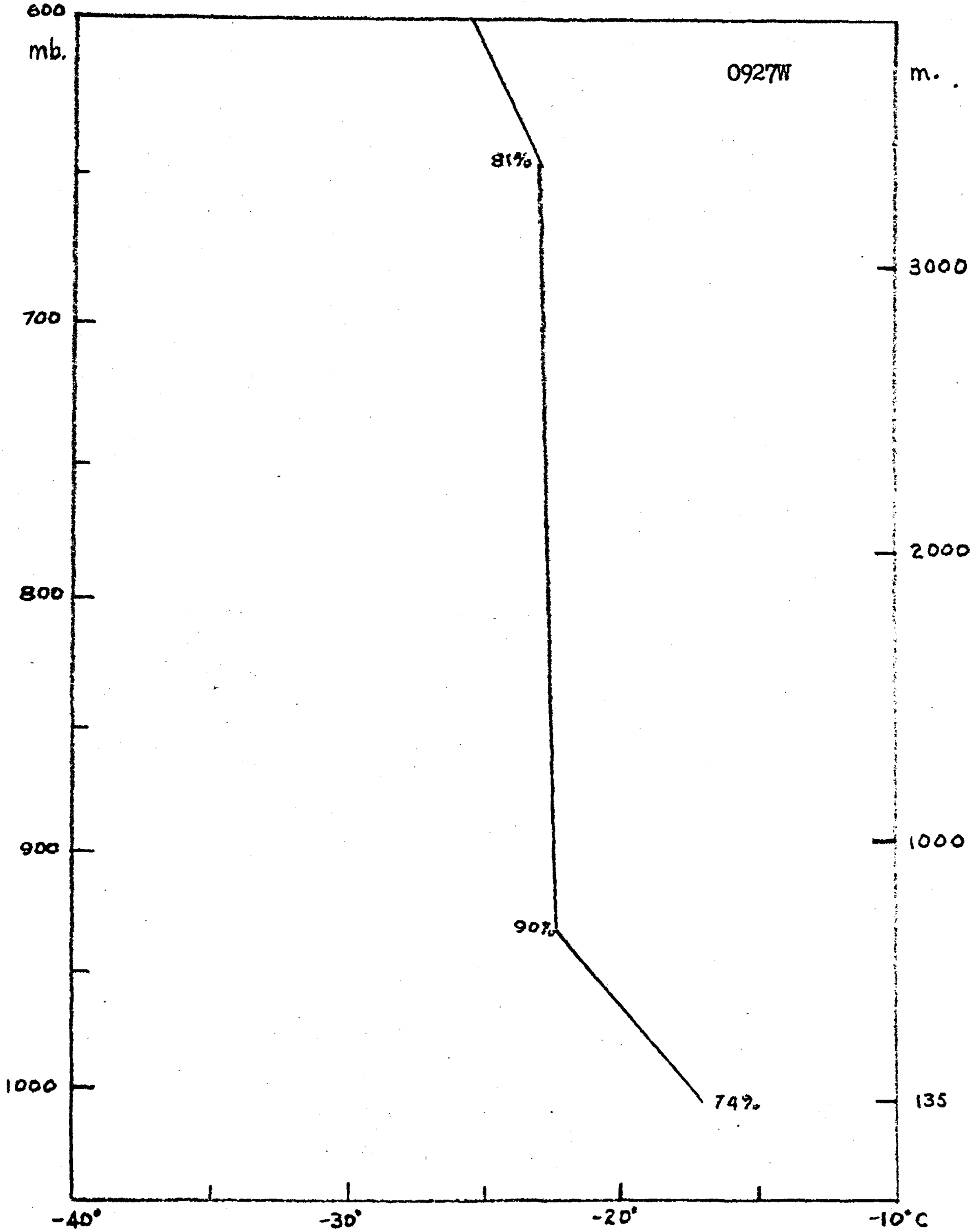


0300W 1/9/38 Sea Level

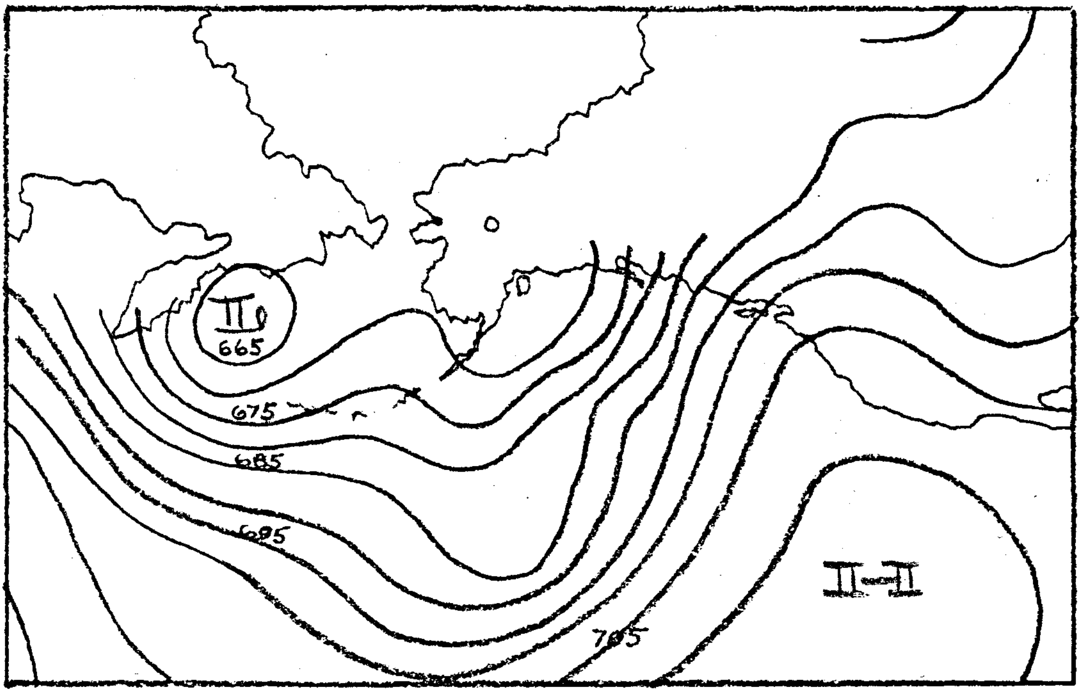
SYNOPTIC MAPS ON JANUARY 9, 1938

Figure 9.



UPPER AIR SOUNDING AT FAIRBANKS, ALASKA, JANUARY 9, 1938

Figure 10.



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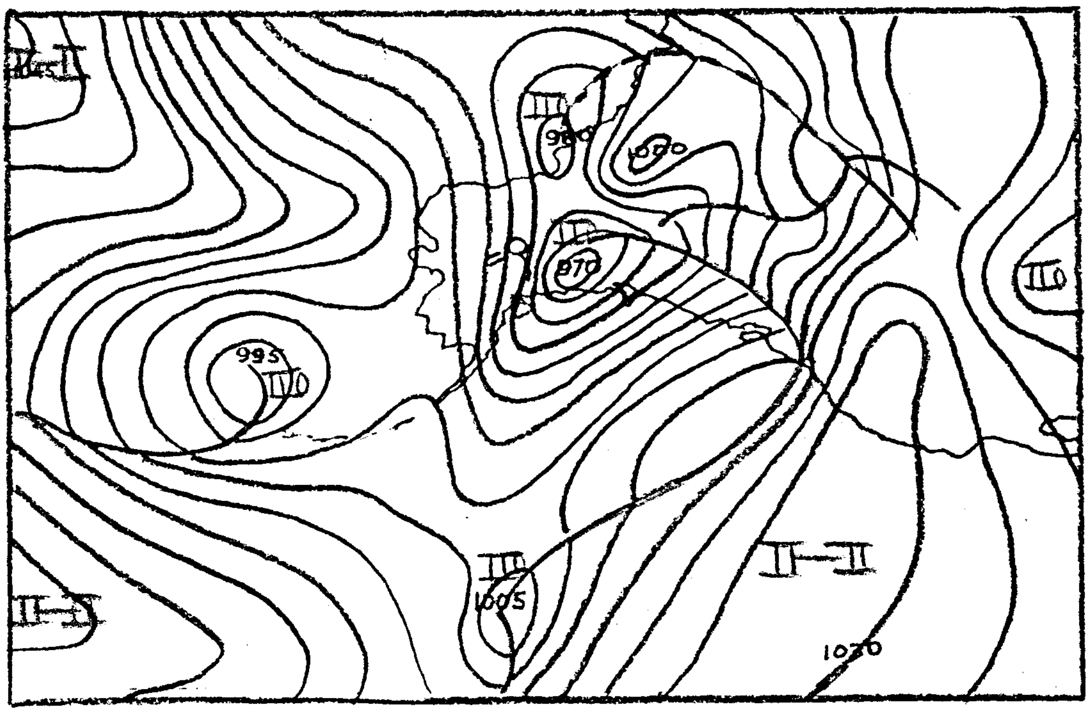


0300W 12/17/36 Sea Level

SYNOPTIC MAPS ON DECEMBER 17, 1936

Figure 11.

except on instruments. Oliver (7) notes that when the temperature at Fairbanks falls below -40° F, extremely dense ice fog forms and persists until the temperature again rises above -40° F. This dense fog is in conjunction with smoke from the chimneys of the city, and Oliver suggests that the fog forms by the collecting of frost on smoke nuclei.

Since ice fog normally forms in the early morning and is dissipated by afternoon, it is wise to plan arctic flights to fields where ice fog is common so that the time of arrival will be during the afternoon hours, when the probability of ice fog is least. Since ice fog is of a local character, it should be possible in most cases to find an alternate airfield, especially one at a higher elevation, which will be free of ice fog, in the event that the planned terminus is fogged in. But when specific information is available that persistent ice fog is possible or is expected at the end of a contemplated flight, the safest procedure would be to postpone the flight.

CHAPTER II

FORECASTING ICE FOG

1. An objective method.

Accurate forecasting of ice fog is not a simple problem. It might almost be said that each station requires its own set of rules. The general conditions under which ice fog may be expected to form are, as previously stated, clear skies, light winds and sub-zero temperatures. Of course sufficient moisture must be present in the air to produce saturation. However, the exact determination of moisture content at low temperatures is not easy with the use of standard meteorological equipment. Small errors in reading the wet-bulb depression are not very significant at moderate temperatures, but at -20° F, for example, an error of 0.5° F in reading the difference between the dry-bulb and wet-bulb temperatures will cause the relative humidity to be in error by 45 per cent. Hair hygrometers are not reliable at low temperatures either (6).

Let us consider an objective method of forecasting ice fog (at Fairbanks, Alaska) based on the statistics of fog frequency with respect to critical values of pressure, temperature, and wind. Table 3 is based on the records at Fairbanks for the months of December, 1936; January and February, 1937; and January and February, 1938. (December, 1937, has been omitted from this table. It will be discussed separately.) Only ice fog has been considered, water fog is classed as a non-occurrence of ice fog.

ICE FOG AT FAIRBANKS, ALASKA

	Ice Fog	No Ice Fog	Totals
Wind $\leqslant$ Beaufort 2 Sea level pressure $>$ 1005 mb. Minimum temp. $<$ -15° F. (All 3 conditions obtain)	53	10	63
Wind $>$ Beaufort 2 Sea level pressure $<$ 1005 Minimum temp. $>$ -15° F (One or more conditions obtain)	8	78	86
Totals	61	88	149

Table 3

Using as a climatological average the figure 37 per cent as the frequency occurrence of ice fog at Fairbanks (see Figure 2) the skill score (11) for forecasting on the basis of the critical values of wind, pressure, and minimum temperature shown in Table 3 may be computed. For the five months included in Table 3, if ice fog had been forecast each time the wind was not greater than Beaufort 2, the sea level pressure was greater than 1005 millibars, and the minimum temperature was below -15° F, a skill score of .75 would have been made. This is a reasonably good score.

But it is necessary to consider the month of December, 1937, shown in Table 4. Here it

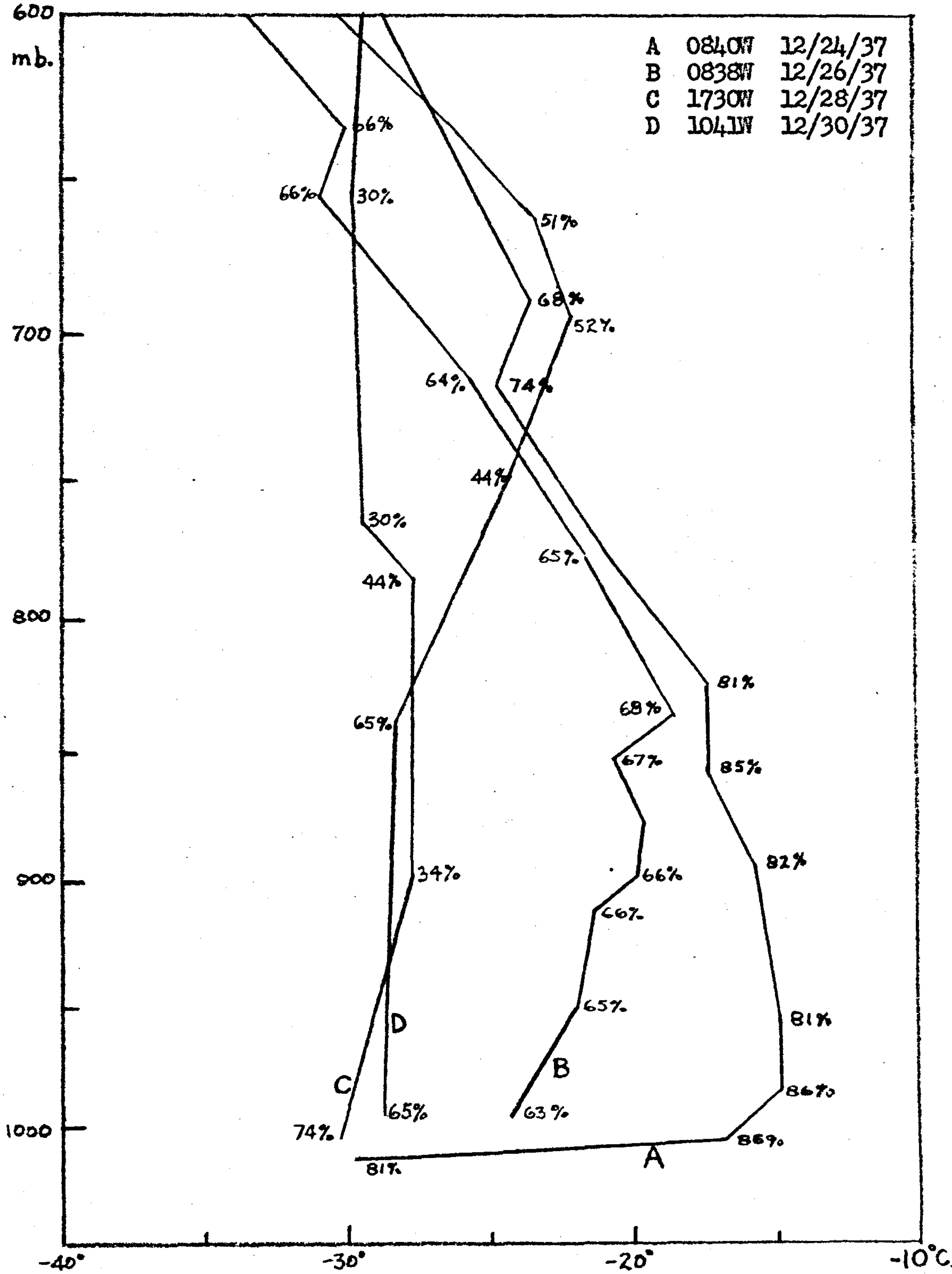
	Ice Fog	No Ice Fog	Totals
Wind $\leqslant$ Beaufort 2 Sea level pressure $>$ 1005 Minimum temp. $<$ -15° F (all 3 conditions obtain)	3	10	13
Wind $>$ Beaufort 2 Sea level pressure $<$ 1005 Minimum temp. $>$ -15° F (One or more conditions obtain)	3	15	18
Totals	6	25	31

Table 4

is seen that using the above system of forecasting for this particular month gives very poor results. The skill score in fact is exactly zero. If Table 4 be combined with Table 3, the skill score will be reduced from .75 to .63, which, though not exactly bad, leaves something to be desired.

2. Supplementing the objective method.

It is necessary to look further for the reason for the forecast failures in December 1937. An examination of the soundings on the 10 days when ice fog should have occurred but did not, shows that six of these days fell within the last seven days of December, and that this was a period when an unusually cold and dry air mass was passing over Fairbanks. Figure 12 shows the change in air mass, beginning with a sounding on December 24 (a day on which ice fog occurred) and indicating the cooling aloft by the large shift in the soundings which followed.



UPPER AIR SOUNDINGS AT FAIRBANKS, ALASKA,

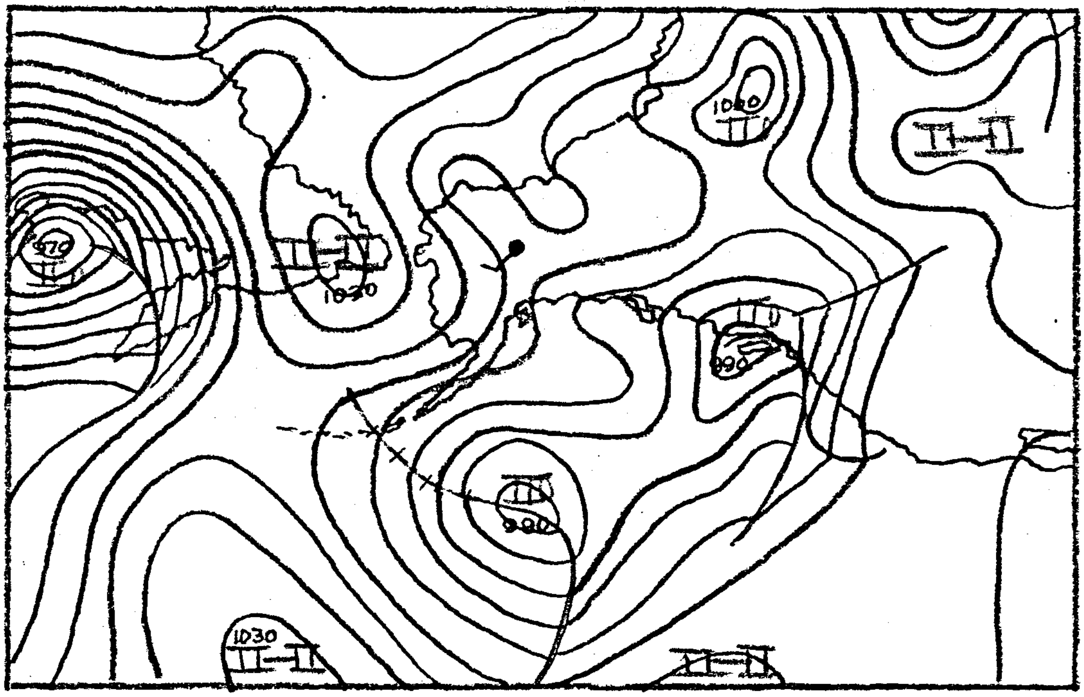
AT THE END OF DECEMBER, 1937.

Figure 12.

It is to be noted that the air is so cold aloft that no sharp surface inversion is formed. From Figures 13 and 14 it can be seen that the weather early in this period was dominated by an anticyclone, which gave way to a series of Pacific cyclones at the end of the period. By December 30 warmer air had begun to move in aloft and by January 1, 1938 ice fog again occurred. By changing the forecast from ice fog to no ice fog during the invasion of exceptionally cold air, the skill score for December will be raised to .46, and the score for the entire six months (December through February in the two winters) will be raised to .70.

A further consideration which should improve forecast accuracy over that to be obtained from the objective method alone is the cloud cover. Ice fog seldom forms when the sky is more than three-quarters obscured by middle or low clouds. A statistical study of the relation between cloud cover and ice fog has not been made in this investigation, but the tendency has been noted for ice fog to occur only when few clouds or when only high clouds are present. Thus if the forecaster supplements his considerations of wind, pressure and minimum temperature with attention to humidity data, air mass characteristics, and cloud cover, his skill score should be acceptably high.

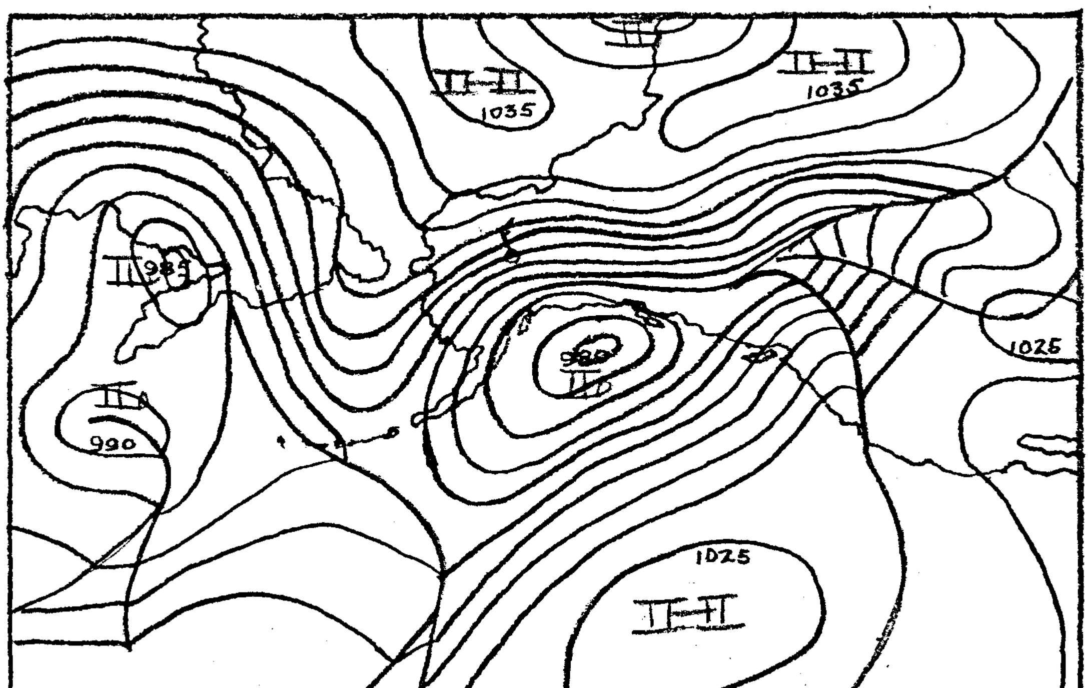
It must be borne in mind that the use of the objective method presented here involves forecasting changes in the synoptic situation, for the critical values of the three weather elements must be applied to the forecast values of these elements. In other words, the skill score for forecasting ice fog will depend at the beginning upon the forecaster's general skill in prognosticating tomorrow's weather map.



0300W 12/26/37 Sea Level

SYNOPTIC MAP ON DECEMBER 26, 1937

Figure 13.



0300W 12/30/37 Sea Level

SYNOPTIC MAP ON DECEMBER 30, 1937

Figure 14.

3. Conclusions.

Summarized here are the conclusions to be drawn from this paper:

(a) Ice fog is a phenomenon of winter time in the arctic and sub-arctic.

(b) It occurs most frequently at stations which lie in valleys or flatlands, under favorable conditions as often as 20 days per month.

(c) It is usual for ice fog to occur in the presence of a polar anticyclone, under a sharp surface temperature inversion.

(d) Because of its shallowness, ice fog usually is not a serious hazard to aircraft operations.

(e) The following objective method of forecasting ice fog is suggested (for Fairbanks):

Forecast ice fog when

(1) The wind will not be greater than Beaufort 2;

(2) The sea level pressure will be greater than 1005 mb.;

(3) The minimum temperature will be less than -15° F.

Forecast no ice fog when

(1) The wind will be greater than Beaufort 2, or

(2) The sea level pressure will be less than 1005 mb., or

(3) The minimum temperature will be greater than -15° F.

(f) To supplement this objective method, the following considerations should be borne in mind:

Ice fog is not likely when

(1) The sky will be more than three-quarters overcast with low or middle clouds;

(2) An exceptionally cold and dry air mass moves over the station;

(3) Humidity readings at the surface clearly indicate saturation of the air will not occur.

(g) It is believed that the objective method would be of value to other stations similar to Fairbanks, with perhaps some modification of the critical values of the three weather elements. If for example, an advance air base should be set up on some arctic flatland, and the forecaster assigned to duty there was not a veteran of the arctic, this objective method would prove of considerable value to him until he acquired the "feel" of his station.

(h) Finally, it is suggested that action should be taken to provide a weather symbol for ice fog in the weather code, for unless this is done, research into the problem of forecasting ice fog will continue to be difficult because of the lack of data.

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